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Well placement can be evaluated by: (1) using ground-water flow and transport models; (2) comparing contaminant mass removed to contaminant mass dissolved in ground water; and (3) applying expert knowledge. P&T system modifications should be considered if any of these methods indicate that different pumping locations or rates will improve system effectiveness.

### **Minimize Ground-Water Stagnation**

Ground-water flow patterns need to be managed to minimize stagnation during P&T operation. Stagnation zones develop in areas where the P&T operation produces low hydraulic gradients (e.g., downgradient of a pumping well and upgradient of an injection well) and in low permeability zones regardless of hydraulic gradient. Ground-water flow modeling can be used to assess ground water and solute velocity distributions, travel times, and stagnation zones associated with alternative pumping schemes. During operation, stagnation zones can be identified by measuring hydraulic gradients, tracer movement, ground-water flow rates (e.g., with certain types of downhole flowmeters or in situ probes), and by modeling analysis. Low permeability heterogeneities should be delineated as practicable during the site characterization and P&T operation. Stagnation zones associated with different pumping schemes are evident in Figure 10.

Once identified, the size, magnitude, and duration of stagnation zones can be diminished by changing pumping (extraction and/or injection) schedules, locations, and rates. Again, flow modeling based on field data may be used to estimate optimum pumping locations and rates to limit ground-water stagnation. An adaptive pumping scheme, whereby extraction/injection pumping is modified based on analysis of field data, should result in more expedient cleanup.

### **Guidance from Modeling Studies**

Several modeling studies have been conducted to examine the effectiveness of alternative extraction and injection well schemes with regard to hydraulic containment and ground-water clean-up objectives (e.g., Freeberg et al., 1987; Satkin and Bedient, 1988; Ahlfeld and Sawyer, 1990; Tiedeman and Gorelick, 1993; Marquis, Jr. and Dineen, 1994; Haggerty and Gorelick, 1994). Although the optimum extraction/injection scheme depends on site-specific conditions, objectives, and constraints, consideration should be given to guidance derived from simulation studies of P&T performance.

A conceptual modeling analysis using FTWORK (Faust et al., 1993) of three alternative pumping strategies for an idealized site with a uniform medium, linear equilibrium sorption, a single non-degrading contaminant, and a continuing release is presented in Figure 11. The plume management strategies include: (1) downgradient pumping, (2) source control with downgradient pumping, and (3) source control with mid-plume and downgradient pumping. As shown, downgradient pumping by itself allows and increases the movement of highly contaminated ground water throughout the flowpath between the release area and the downgradient recovery well. This alternative results in expansion of the highly contaminated plume and makes it more difficult to achieve cleanup. The importance of source control is clearly demonstrated by comparing the management alternatives. Source control pumping prevents continued offsite migration and thereby facilitates downgradient cleanup of contaminated ground water.

The combined source control, mid-plume, and downgradient pumping alternative reduces the flowpath and travel time of contaminants to extraction wells and diminishes the impact of processes which cause tailing. As such, with more aggressive P&T, cleanup is achieved more quickly and the volume of ground water that must be pumped for cleanup is less than for the other alternatives.

The effectiveness of seven injection/extraction well schemes shown in Figure 12 at removing a contaminant plume was evaluated by Satkin and Bedient (1988) using the MOC transport model (Konikow and Bredehoeft, 1989). The performance of each scheme was assessed for eight different hydrogeologic conditions, which were simulated by varying maximum drawdown, dispersivity, and regional hydraulic gradient. Effectiveness was judged based on simulated cleanup, flushing rate, and the volume of water requiring treatment. Findings of this study include (Satkin and Bedient, 1988): (1) multiple extraction wells located along the plume axis (the center line scheme) reduce clean-up time by shortening contaminant travel paths and allowing higher pumping rates; (2) the three-spot, double-cell, and doublet schemes were effective under low hydraulic gradient conditions, but require onsite treatment and reinjection; (3) the three-spot pattern outperformed the other schemes for simulations incorporating a high regional hydraulic gradient; and, (4) the center line pattern was effective under all simulated conditions. Andersen et al. (1984) and Satkin and Bedient (1988) showed that the five-spot pattern (Figure 12) may be a relatively inefficient scheme for cleanup.

Brogan (1991) and Gailey and Gorelick (1993) used simulations to demonstrate that the best single recovery well location is somewhat downgradient of a plume's center of mass. The optimum location (requiring the lowest pumping rate) for a single extraction well to remediate a plume within a given time period increases in distance downgradient from the center of contaminant mass with increasing remediation time (Gailey and Gorelick, 1993; Haggerty and Gorelick, 1994). Thus, optimum pumping locations and rates depend on the specified clean-up time frame.

The relative merits of conventional extraction/injection well schemes, in-situ bioremediation, and P&T enhanced by injecting oxygenated water to stimulate biodegradation for containing and cleaning up a hypothetical naphthalene plume in a uniform aquifer were examined by Marquis and Dineen (1994). Nineteen remediation alternatives were modeled using BIOPLUME II (Rifai et al., 1987), a modified version of the MOC code (Konikow and Bredehoeft, 1989) that simulates oxygen transport and oxygen-limited biodegradation. Key findings made by Marquis and Dineen (1994) include the following: (1) ground-water extraction was more effective at preventing offsite migration than bioremediation; (2) P&T enhanced by injecting highly oxygenated water (with 50 mg/L dissolved oxygen) provided the most effective plume control and cleanup; (3) greater contaminant mass reductions occurred when extraction or injection wells were located in the more contaminated portions of the plume; (4) cleanup is hastened by minimizing the distances that contaminants must travel to extraction wells or that dissolved oxygen must travel to reach degradable contaminants; (5) to maximize containment, P&T schemes should be designed to produce convergent flow toward a central extraction location and to minimize divergent flow along the plume periphery; and (6) extraction/injection schemes should be designed to minimize the presence of upgradient and intraplume stagnation areas.

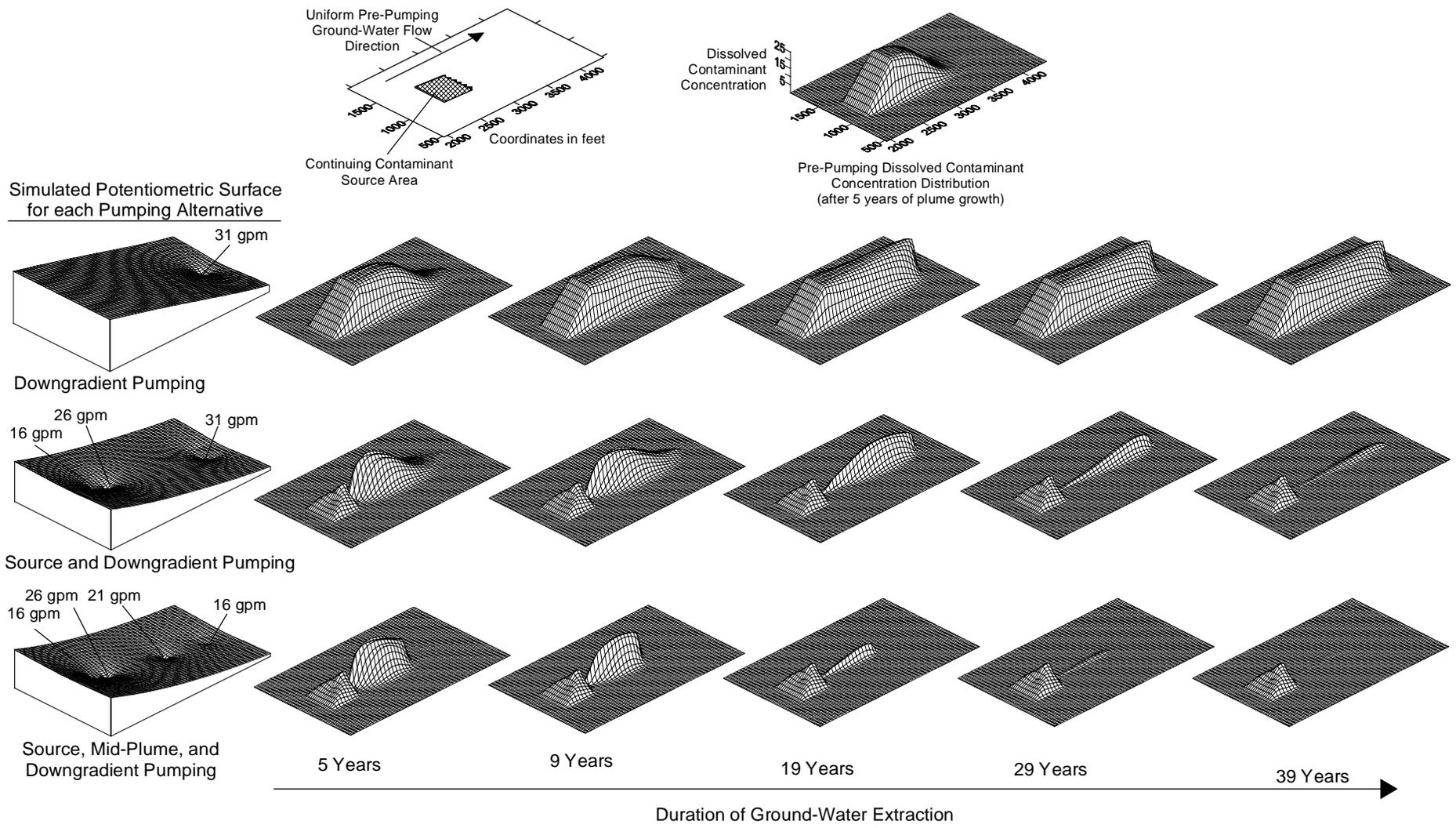


Figure 11. Results of FTWORK (Faust et al., 1993) simulation analysis of three P&T alternatives for an idealized site (with uniform media, linear equilibrium sorption, and a single non-degrading contaminant) showing dissolved contaminant concentrations with time of pumping.